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## **LIGHT EMITTING DEVICE AND METHOD**

### **FIELD OF THE INVENTION**

This invention relates to semiconductor light emission, and, more particularly to a method and device for producing controlled light emission, and which is also simultaneously capable of electrical signal amplification.

### **BACKGROUND OF THE INVENTION**

A part of the background hereof lies in the development of light emitters based on direct bandgap semiconductors such as III-V semiconductors. Such devices, including light emitting diodes and laser diodes, are in widespread commercial use.

Another part of the background hereof lies in the development of wide bandgap semiconductors to achieve high minority carrier injection efficiency in a device known as a heterojunction bipolar

transistor (HBT), which was first proposed in 1948 (see e.g. U.S. Patent 2,569,376; see also H. Kroemer, "Theory Of A Wide-Gap Emitter For Transistors" Proceedings Of The IRE, 45, 1535-1544 (1957)). These transistor devices are capable of operation at extremely high speeds. An InP HBT has recently been demonstrated to exhibit operation at a speed above 500 GHz.

It is among the objects of the present invention to provide devices and methods for producing controlled light emission, and to also provide devices capable of simultaneous control of optical and electrical outputs.

## SUMMARY OF THE INVENTION

An aspect of the present invention involves a direct bandgap heterojunction transistor that exhibits light emission from the base layer. Modulation of the base current produces modulated light emission. [As used herein, "light" means optical radiation that can be within or outside the visible range.]

A further aspect of the invention involves three port operation of a light emitting HBT. Both spontaneous light emission and electrical signal output are modulated by a signal applied to the base of the HBT.

In accordance with one embodiment of the invention, a method is set forth for producing controllable light emission from a semiconductor device, including the following steps: providing a heterojunction bipolar transistor device that includes collector, base, and emitter regions; and applying electrical signals across terminals coupled with the collector, base, and emitter regions to cause light emission by radiative recombination in the base region. In a form of this embodiment, the step of applying electrical signals includes applying a collector-to-emitter voltage and modulating light output by applying a modulating base current.

In accordance with another embodiment of the invention, a device is set forth having an input port for receiving an electrical

input signal, an electrical output port for outputting an electrical signal modulated by the input signal, and an optical output port for outputting an optical signal modulated by the input signal, the device comprising a heterojunction bipolar transistor device that includes collector, base, and emitter regions, the input port comprising an electrode coupled with the base region, the electrical output port comprising electrodes coupled with the collector and emitter regions, and the optical output port comprising an optical coupling with the base region.

In accordance with a further embodiment of the invention, a semiconductor laser is set forth, including: a heterojunction bipolar transistor structure comprising collector, base, and emitter of direct bandgap semiconductor materials; an optical resonant cavity enclosing at least a portion of the transistor structure; and means for coupling electrical signals with the collector, base, and emitter regions to cause laser emission from the device.

Further features and advantages of the invention will become more readily apparent from the following detailed description when taken in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a simplified cross-sectional diagram, not to scale, of a device in accordance with the invention, and which can be used in practicing an embodiment of the method of the invention.

Figure 2 is a top view of the Figure 1 device layout for an embodiment of the invention.

Figure 3 is CCD microscopic view of a test device in accordance with the invention.

Figure 4 is a simplified schematic diagram of a three port device in accordance with an embodiment of the invention.

Figure 5 is a graph of the common emitter output characteristics of the test device, also showing the observed light emission.

Figure 6, which includes oscilloscope traces 6A and 6B, show, respectively, the input reference and output modulated light waveforms for the test device.

Figure 7 is a graph showing light output as a function of base current for the test device.

Figure 8 illustrates an embodiment of the invention that includes a light reflector.

Figure 9 illustrates a laser device in accordance with an embodiment of the invention.

Figure 10A shows a portion of a device in accordance with an embodiment of the invention, employing one or more quantum wells.

Figure 10B shows a portion of a device in accordance with an embodiment of the invention, employing one or more regions of quantum dots.

Figure 11 is a simplified cross-sectional diagram, not to scale, of a vertical cavity surface emitting laser in accordance with an embodiment of the invention.

Figure 12 is a simplified cross-sectional diagram, not to scale, of a vertical cavity surface emitting laser in accordance with a further embodiment of the invention.

Figure 13 is a simplified diagram of a display array in accordance with an embodiment of the invention.

## DETAILED DESCRIPTION

Figure 1 illustrates a device in accordance with an embodiment of the invention and which can be used in practicing an embodiment of the method of the invention. A substrate 105 is provided, and the following layers are disposed thereon: subcollector 110, collector 130, base 140, emitter 150, and cap layer 160. Also shown are collector metallization (or electrode) 115, base metallization 145, and emitter metallization 165. Collector lead 117, base lead 147, and emitter lead 167 are also shown. In a form of this embodiment, the layers are grown by MOCVD, and the collector layer 130 comprises 3000 Angstrom thick n-type GaAs,  $n = 2 \times 10^{16} \text{ cm}^{-3}$ , the base layer 140 comprises 600 Angstrom thick p+ carbon-doped compositionally graded InGaAs (1.4% In),  $p = 4.5 \times 10^{19} \text{ cm}^{-3}$ , the emitter layer 150 comprises 800 Angstrom thick n-type InGaP,  $n = 5 \times 10^{17} \text{ cm}^{-3}$ , and the cap layer comprises 1000 Angstrom thick n+ InGaAs,  $n = 3 \times 10^{19} \text{ cm}^{-3}$ .

This embodiment employs a fabrication process sequence which includes e-beam defined Ti/Pt/Au emitter contacts (145), a self-aligned emitter etch, a self-aligned Ti/Pt/Au base metal deposition, a base-collector etch, and collector metal deposition. A bisbenzocyclobutene (BCB) based etch-back process is employed for “backend” fabrication (i.e., to render the electrode and contact formation on the top of the transistor).

For conventional PN junction diode operation, the recombination process is based on both an electron injected from the n-side and a hole injected from the p-side, which in a bimolecular recombination process can be limited in speed. In the case of HBT light emission hereof, the base "hole" concentration is so high that when an electron is injected into the base, it recombines (bimolecular) rapidly. The base current merely re-supplies holes via relaxation to neutralize charge imbalance. For a heterojunction bipolar transistor (HBT), the base current can be classified into seven components, namely: (1) hole injection into the emitter region ( $i_{Bp}$ ); (2) surface recombination current in the exposed extrinsic base region ( $i_{Bsurf}$ ); (3) base ohmic contact recombination current ( $i_{Bcont}$ ); (4) space charge recombination current ( $i_{Bscr}$ ); (5) bulk base non-radiative recombination current due to the Hall-Shockley-Reed process (HSR) ( $i_{BHSR}$ ); (6) bulk base Auger recombination current ( $i_{BAug}$ ); and (7) bulk base radiative recombination current ( $i_{Brad}$ ).

For a relatively efficient HBT with ledge passivation on any exposed base region, the surface recombination current can be reduced significantly. Hence, the base current and recombination lifetime can be approximated as primarily bulk HSR recombination, the Auger process, and radiative recombination. The base current expressed in the following equation (1) is then related to excess minority carriers,  $\Delta n$ , in the neutral base region, the emitter area,  $A_E$ , the charge,  $q$ , and the base recombination lifetime,  $\tau_n$  as

$$i_B = i_{BHSR} + i_{BAUG} + i_{Brad} = qA_E \Delta n / \tau_n \quad (1)$$

The overall base recombination lifetime,  $\tau_n$ , is related to the separate recombination components of Hall-Shockley-Read,  $\tau_{HSR}$ , Auger,  $\tau_{AUG}$ , and radiative recombination,  $\tau_{rad}$ , as

$$\tau_n = (1/\tau_{HSR} + 1/\tau_{AUG} + 1/\tau_{rad})^{-1} \quad (2)$$

The light emission intensity  $\Delta I$  in the base is proportional to  $i_{Brad}$  and is related to the minority carrier electron with the majority hole over the intrinsic carrier concentration,  $(np-n_i^2)$ , in the neutral base region and the rate of radiative recombination process,  $B$ , set forth in Equation (3) below, where the hole concentration can be approximated as equal to base dopant concentration,  $N_B$ . The radiative base current expressed in equation (3) is then related to excess minority carriers,  $\Delta n$ , in the neutral base region, and the base recombination lifetime,  $\tau_{rad}$  as

$$i_{Brad} = q A_E B (np - n_i^2) = q A_E B n p = q A_E \Delta n (BN_B) = q A_E \Delta n / \tau_{rad} \quad (3)$$

For a high speed HBT, it is easy to predict that the base recombination lifetime can be less than half of the total response delay time. Hence, the optical recombination process in the base should be at least two times faster than the speed of the HBT. In other words, HBT speed, which can be extremely fast, is limiting.

Figure 2 shows the top view of the device layout and Figure 3 shows a silicon CCD microscopic view of a fabricated  $1 \times 16 \mu\text{m}^2$  HBT test device with light emission (white spots) from the base layer under normal operation of the transistor.

In typical transistor operation, one of the three terminals of a transistor is common to both the input and output circuits. This leads to familiar configurations known as common emitter (CE), common base (CB), and common collector (CC). The common terminal (often ground reference) can be paired with one or the other of the two remaining terminals. Each pair is called a port, and two pairs for any configurations are called a two-port network. The two ports are usually identified as an input port and as an output port. In accordance with a feature hereof as illustrated in Figure 4, a third port, namely an optical output port, is provided, and is based on (recombination-radiation) emission from the base layer of the HBT light emitter in accordance with an embodiment of the invention. For the HBT of Figure 1 operated, for example, with a common emitter configuration (see Figure 4) when an electrical signal is applied to the input port (Port 1), there results simultaneously an electrical output with signal amplification at Port 2 and optical output with signal modulation of light emission at Port 3.

The common emitter output characteristics of the test version of the Figure 1, 2 device are shown in Figure 5. The DC beta gain  $\beta = 17$  at  $i_b=1$  mA. For  $i_b=0$  mA ( $i_c=0$  mA), no light emission is observed using a silicon CCD detector. For  $i_b=1$  mA ( $i_c=17.3$  mA), weak light emission is observed from the base layer. For  $i_b=2$  mA ( $i_c=33$  mA), stronger light emission is observed, and still stronger for  $i_b=4$  mA ( $i_c=57$  mA). The spontaneous light emission because of radiative recombination in the base of the HBT in transistor operation is evident.

An output light modulation test was performed for this embodiment. A pattern generator (Tektronix Function Generator) produces an AC signal with

peak-to-peak amplitude of 1 V. A bias tee combines this AC signal with a DC bias voltage of 1.1V from a DC supply. The InGaP/GaAs HBT turn-on voltage is  $V_{BE} = 1.5V$ . The HBT transistor's emission area (open space of the base region) is less than  $1\text{-}\mu\text{m} \times 2\text{-}\mu\text{m}$ . The light from the small aperture (most of the HBT light is obscured in this test) is coupled into a multimode fiber probe with a core diameter of  $25\mu\text{m}$ . The light is fed into a Si APD detector with a 20-dB linear amplifier. A sampling oscilloscope displays both the input modulation signal and the output light signal. The optical emission wavelength is around 885nm due to the compositionally graded InGaAs base (1.4% In). Figure 6 shows the input (lower trace) reference and output (upper trace) light waveforms when the HBT is modulated at 1MHz (Fig. 6A) and also at 100KHz (Fig. 6B). The output signal has a peak-to-peak amplitude of  $375\mu\text{V}$  at 1MHz and  $400\mu\text{V}$  at 100KHz. These data show that the output light signal tracks the input signal, showing clearly that the HBT is a light-emitting transistor (LET) that operates at transistor speed.

The output peak-to-peak amplitude,  $V_{pp}$ , which is directly proportional to the light emission intensity,  $\Delta I_{out}$ , as a function of base current, is shown in Figure 7. The nonlinear behavior may be due to beta compression because of heating and the fact that the device geometry has not yet been optimized for light emission (as well as lateral biasing effects). Nevertheless, these measurements, i.e.,  $\Delta I_{out}$  (light intensity) vs.  $\Delta i_b$  ( $i_b = 0$  to  $5\text{mA}$ ), demonstrate the HBT as a three terminal controllable light source.

It will be understood that other configurations and material systems can be used, including, as examples, GaAs and GaN based HBTs, or other direct bandgap material systems.

Figure 8 illustrates use of the three terminal light emitting HBT 810 in conjunction with a reflector cup 820 for enhancing light collection and directionality.

Figure 9 illustrates the three terminal light emitting HBT, 910, in a lateral cavity, represented at 920, for operation as a lateral gain guided laser. The lateral cavity may be defined, for example, by cleaved edges on and near the light emitting region.

Figure 10A shows the use of one or more quantum wells, 141, 142, in the base region 140 of the Figure 1 device (or other embodiments), these quantum wells being operative to enhance the recombination process for improved modulation and/or to tailor the spectral characteristics of the device.

Figure 10B shows use of one or more regions of quantum dots, 143, 144, in the base region 140 of the Figure 1 device (or other embodiments), these quantum dot regions being operative to enhance the recombination process for improved modulation and/or to tailor the spectral characteristics of the device.

Figure 11 shows a vertical cavity surface emitting laser in accordance with an embodiment of the invention which employs light emission from the base region of an HBT. A substrate 1105 is provided, and the following layers are provided thereon. DBR reflector layer 1108, subcollector 1110, collector 1130, transition layer 1133, base 1140, emitter 1150, emitter cap layer 1160 and top

DBR reflector layer 1168. Also shown are collector metallization 1115, base metallization 1145, and emitter metallization 1165. Collector lead 1117, base lead 1147, and emitter lead 1167 are also shown. In a form of this embodiment, the layers are grown by MOCVD, the substrate 1105 is a semi-insulating InP substrate, subcollector 1110 is n+ InGaAs, collector 1130 is n- InP, the base 1140 is a p+ InGaAs layer with a quantum well, the emitter 1150 is n-type InP, and the emitter cap 1160 is n+ InGaAs. Also, the transition layer is an n-type quaternary transition layer, for example InGaAsP. In this embodiment, the reflector layers 1108 and 1168 are multiple layer DBR reflectors, which can be spaced apart by suitable distance, such as a half wavelength. In operation, as before, with signals applied in three terminal mode, modulation of the base current produces modulated light emission, in this case vertically emitted laser light represented by arrow 1190. As above, it will be understood that other configurations and material systems can be used, including, as examples, GaAs and GaN based HBTs, or other direct bandgap material systems.

Figure 12 shows a further embodiment of a vertical cavity surface emitting laser, which has a Bragg reflector as close as possible to the collector and with elimination of intervening lower gap absorbing layers between the DBRs. In particular, in Figure 12 (which has like reference numerals to Figure 1 for corresponding elements), the lower DBR is shown at 111, and an upper DBR is shown at 141. Arrow 190 represents the optical standing wave of the VCSEL. The DBR 141 can be a deposited Si-SiO<sub>2</sub> Bragg reflector. A further reflector can also be provided on the top of emitter 150.

Figure 13 shows a display 1310 using an array of light-emitting HBTs 1331, 1332, 1341, etc. The light output intensities can be controlled, as previously described. Very high speed operation can be achieved.

The principles hereof can also potentially have application to indirect bandgap materials (such as Ge and Si) in an HBT with a heavily doped base region, and with an optical port that is optically coupled with the base region. The light produced will generally be of less intensity than that produced by the direct bandgap HBT light emitters hereof. However, it may be useful to have this light generating and coupling capability in Ge-Si systems for various applications, including devices having one or more quantum wells and/or one or more quantum dot regions for enhancing recombination.